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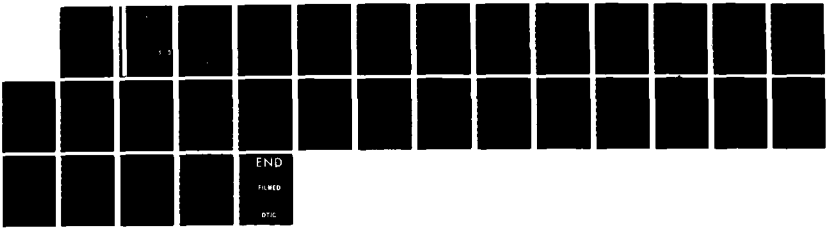

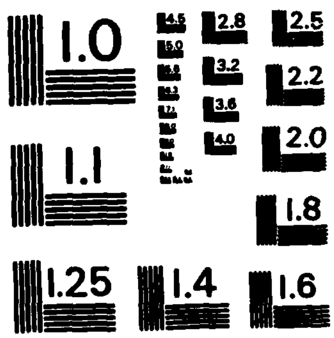

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Structures Technical Memorandum 405

DETERMINATION OF THE DEPENDENCE OF ULTRASONIC SHEAR WAVE TRANSIT TIMES ON TEMPERATURES, STRESS AND FREQUENCY

by

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SUMMARY

The practical use of ultrasonics to determine residual stress requires a technique to separate the effects of texture and stress. This memorandum reports the results of a preliminary study of the temperature, stress and frequency dependence of ultrasonic shear wave transit times in a 2024T4 aluminium alloy sample. The acoustoelastic constant, the relative temperature coefficient and the texture induced anisotropy were found to be of the order 10^{-4}/MPa 10^{-3}/K and 10^{-2} respectively.

Two techniques of separating the effects of texture and stress were investigated. These were the stress dependence of temperature coefficient and the frequency dependence of the birefringence. It was found that within the precision of measurement, there was no stress dependence of the temperature coefficient for shear wave polarization parallel or perpendicular to the stress. The frequency dependence had a complex behaviour which is not understood and will be the subject of further study.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

CONTENTS

1. INTRODUCTION

A more detailed knowledge of the residual stresses in aircraft structures is highly desirable as these stresses can affect, among other things, the ultimate strength and the fatigue life of the structure. The residual stresses of interest here are those stresses that are uniform over several millimetres and are therefore usually called residual macro-stresses. A wide variety of techniques exist which enable a measurement of residual stresses to be made. Coyle [1] has summarized and categorized the techniques into four classes. These are ultrasonic, diffraction, magnetic, and hole-drilling methods. The two most common methods are hole drilling and X-ray diffraction. However both have disadvantages as hole drilling is semi-destructive and X-ray diffraction is restricted to surface layers.

Allen et al [2] have noted that ultrasonic methods have potential as they are nondestructive and are sensitive to residual stresses in the bulk. Most ultrasonic methods rely on the acoustoelastic effect i.e., the difference in ultrasonic velocities between stressed and unstressed states of the material. The utilization of this effect has enabled reliable measurements of applied stresses to be made. Typical of these are the measurements of Schneider and Goebbels [3], and Clark et al. [4]. However whilst residual stresses have been measured e.g. Fukuoda et al [5], and Schneider et al [6], there is still a need for further theoretical and experimental development.

The main difficulty associated with the acoustoelastic ultrasonic method of measuring residual stress is an incomplete understanding of the numerous other effects e.g. texture, dispersion, diffraction, temperature and transducer coupling which have an influence on ultrasonic velocity measurements. For the above reasons, a systematic study of the use of ultrasonics in the measurement of residual stresses was commenced.

2. PRINCIPLES OF STRESS MEASUREMENTS

The ratio of the stress induced velocity changes to the mean velocity for both longitudinal and transverse waves is of the order 10^{-4}/MPa. This limits the applicability of longitudinal waves for the determination of residual stress because of the precision required in length measurment and temperature stability. For example an uncertainty of 10^{-4} in length and 1K in temperature results in a stress uncertainty of approximately 10MPa in aluminium. On the other hand, shear wave birefringence largely eliminates these differences. In this method the difference in transit times between the two polarization components is determined. This difference, when divided by the mean transit time is largely independent of both temperature and length.

For propagation perpendicular to the direction of principal stress the relationship between transit time and stress can be obtained from equations given by Allen and Sayers [7]:

$$\frac{t_1 - t_2}{t_0} = \frac{T}{2\mu}\left(1 + \frac{n}{4\mu}\right)$$

where t_1 and t_2 refer to transit times for shear wave polarization parallel and perpendicular to the direction of stress, t_0 is the transit time at zero stress which approximates to $(t_1 + t_2)/2$; T is the uniaxial stress (+ve for compressive stress), μ is one of the second order Lame elastic constants and n is one of the third order Murnaghan elastic constants. This equation was derived assuming an isotropic material. Unfortunately most practical materials are anisotropic, in that they are composed of non-randomly orientated crystallites (texture).

3. TEXTURE

The texture in a material gives rise to an intrinsic birefringence independent of stress and of similar or greater magnitude to stress induced birefringence. It is the separation of these two components of birefringence which is the major obstacle to the practical use of ultrasonics for the determination of residual stresses. There have been three techniques reported in the literature that purport to allow separation of the texture and the stress birefringence.

These are:

1. the frequency dependence of biregringence
2. the stress dependence of the temperature coefficient of velocity
3. texture independent combinations of the longitudinal ans shear wave velocities.

These techniques have been discussed elsewhere (Rumble and Sparrow [8]). The first technique has received the most attention in the literature. This memorandum reports on a preliminary study using the first two techniques.

4. EXPERIMENTAL

The measurement of transit times was achieved by digitizing the voltage output from a broadband shear transducer. A block diagram of the instrumentation used is shown in Figure 1. A discrete Fast-Fourier-Transform-based computer algorithm was used to calculate the transit times between the successive return echoes. Details of the instrumentation and analysis procedures are given in reference 9. The transducer used was a Panametrics model V157, 5MHz broadband shear wave transducer, with an active PZT element of 0.125 inch diameter. The approximate direction of shear motion was determined using a passive polarization analyzer consisting of a set of parallel glass plates, as suggested by Hsu and

Sachse [10] and Proctor [11]. Ultrasonic coupling between transducer and specimen was achieved using a thin layer of viscoelastic fluid (Panametrics shear wave couplant). The transducer was held in a clamp which enabled rotation relative to the specimen and with the capability of changing the clamping pressure.

The specimen was 2024T4 aluminium alloy of dimensions 50 x 50 x 10 mm. The ultrasonic propagation direction was through the 10 mm thickness direction. The transducer was placed in the middle of the 50 x 50 mm face to minimize side reflections. From a measurement of the transit time as the transducer was rotated, the principal directions of texture were identified, these being the polarization directions which gave maximum and minimum transit times. This was confirmed using optical inspection following polishing and macroetch. The directions were parallel and perpendicular to the sides of the specimens and the extrusion direction.

Measurements of the transit time were made as a function of frequency, stress and temperature. Stress was applied parallel to the extrusion direction and measurements of the transit times were taken for polarizations parallel and perpendicular to the stress direction. The experiment was performed in a temperature controlled room over a range from 289 to 301K. The temperature was controlled to ±0.5K.

5. RESULTS

The transit times as a function of temperature, stress and frequency for the two polarizations are presented in Tables 1-8. These data are derived from the averaging of ten successive measurements of the transit times between echoes 1 to 2. No attempt was made to remove erroneous values (e.g. from A/D converter dropouts, trigger jitter or other causes) and consequently the quoted values in brackets in the above Tables may not always be valid. Furthermore no corrections have been made for the effects of diffraction. (Papadakis [13,14], Allen et al [15]).

A typical variation of transit time for a given frequency is plotted in Figure 2 as a function of temperature and stress. The Figure indicates a linear relationship between transit times and temperature for stresses over the range 0 to 68 MPa for both polarizations. A calculation of the least squares linear fit of transit times against temperature for each frequency, stress and polarization has been carried out. These results have also been included in Tables 1-8. Using these best fit equations, the values of transit times at 22K were calculated for each frequency, stress and polarization and are given in Table 9. Figure 3 shows the change from the zero stress level of the transit times plotted as a function of stress for the two polarizations and two frequencies calculated from the data in Table 9. While the values for polarizations perpendicular to stress are small they indicate a trend towards increased transit times. However for polarizations parallel to stress a linear relationship is clearly indicated, with transit times decreasing with increasing compressive stress. Also given in Table 9 are the differential transit times and the results of a least squares linear fit to the differential transit times against stress. (The differential transit time is the transit time difference between the two polarizations). A typical example of the differential transit time as a function of stress is plotted in Figure 4 and indicates a strong linear relationship.

Subsequent to the calculation of the least squares linear fits of transit times to temperature and stress independently, a multiple linear regression fit of transit time to temperature and stress at each frequency was performed using a HP85 software package. This software package also enabled a calculation of the standard error in temperature times stress term in the transit time dependence. The results of these calculations are given in Tables 10 - 13.

6. DISCUSSION

The measurements and calculations presented here indicate the complexity of ultrasonic, velocity-based, stress determinations. The results show that there are linear relationships between temperature and transit time, and stress and transit times for shear wave polarization parallel to stress. However, whilst comparisons of the temperature and stress coefficients at different frequencies are complicated by the lack of diffraction corrections, there does not appear to be a simple relationship between these coefficients and frequency.

The graph of differential transit times as a function of stress (Figure 4) illustrates that the technique is capable of measuring applied stresses if a calibration could be performed. It would also be possible to create a map of the residual stress in a region of a sample if it is assumed the texture is constant over the region and a residual stress free region is available as a zero reference. It would also be necessary to ensure the sample faces were parallel, and the sample-transducer coupling was constant. Figure 4 also illustrates that the differential transit time at zero applied stress could be used as a measure of texture in the absence of residual stress. It can be seen from Table 9 that for the sample used, the zero applied stress differential transit time was of the order of 1 percent of the mean transit time whereas the change in the differential transit time for a 10MPa increase in stress was of the order of 0.05 percent. This highlights the difficulty in ensuring that a change in texture, or a change in sample-transducer coupling conditions is not incorrectly attributed to a residual stress change.

The nonlinear variation of the coefficients in Table 9 with frequency is also an area of concern, as Mahadevan [15], and Arora and James [16] have reported a linear variation of differential transit time at a given stress with frequency. Although no diffraction corrections have been made, it appears unlikely, given the form of the diffraction correction calculated by Papadakis [12], that a correction could be made to compensate for the variations from nonlinearity observed.

Further effort is being directed at incorporating a diffraction correction and to understand in more detail the frequency characteristics of the broadband transducer, and the transducer-sample interface.

The results reported here also reveal that, within the precision of the measurements made, there is no stress dependence in the temperature coefficient of transit times for shear wave polarization parallel and perpendicular to the stress. Salama and Ling [17] have reported that the relative change in the temperature coefficient as a function of stress is texture independent for longitudinal ultrasonic waves. They also found that for shear wave polarizations parallel to the direction of stress, the variation of the temperature dependence of the transit times with stress was within the precision of the experimental measurements. However they conclude that there could be stress dependence in the temperature dependence for shear wave polarizations perpendicular to stress. The present work indicates that this is not so, and that the temperature coefficient of shear wave transit times cannot be used as a measure of stress.

A comparison of the frequency dependence of the temperature coefficient of the transit times for the shear wave polarizations parallel and perpendicular to stress reveals that for frequencies below 4MHz there are significant differences in temperature dependence. This would mean that in a practical application of residual stress determination based on the frequency dependence of the birefringence, the temperature would have to be stabilized and measured to ensure accurate determination. The lack of the need for temperature stability and measurement was one of the advantages of birefringence based techniques. To maintain this advantage it would be necessary to ensure that the frequency dependence of the temperature dependence is the same for both shear wave polarizations. Fortunately, in the sample used in the tests reported here, the temperature dependence of the two polarizations are within the limits of experimental error for frequencies above 4MHz.

7. CONCLUSION

The results presented here show a linear relationship between temperature and transit time, and stress and transit time. Within the precision of measurement there is no stress dependence of the temperature coefficient of the transit time for shear wave polarization parallel or perpendicular to the stress. This is in contrast to the behaviour suggested by Salama and Ling [17]. The transit times and the stress coefficients have a complex behaviour as a function of frequency, which is not understood and thus will be the subject of further theoretical and experimental study.

The acoustoelastic constant for the 2024T4 aluminium alloy sample was found to be of the order of 10^{-4}/MPa. The relative temperature coefficients and the texture induced anisotropy were found to be of the order 10^{-3}/K and 10^{-2} respectively. These magnitudes illustrate the relative insensitivity of transit time to stress compared to temperature and texture and indicate the difficulty in separating the effects of texture and stress.

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TABLE 1. TRANSIT TIMES AT ZERO STRESS AS A FUNCTION OF FREQUENCY AND TEMPERATURE.

	MEASURED VALUES			CALCULATED VALUES	
TEMPERATURE	16.4C	22.1C TRANSIT TIMES	27.1C	OC TRANSIT TIME	TEMPERATURE COEFFICIENT NANOSEC/C
FREQUENCY MHz					
2.73	6319.6(.2)	6339.7(.1)	6356.7(.2)	6262.8(0.8)	3.5 (0.04)
3.13	6323.1(.6)	6337.7(.1)	6355.4(.1)	6272.9(6.3)	3.0*(0.3)
3.52	6333.3(.1)	6342.3(.1)	6357.8(.1)	6294.8(9.7)	2.3*(0.4)
3.91	6321.0(.1)	6337.0(.1)	6352.0(.2)	6273.4(1.2)	2.9 (0.1)
4.30	6303.6(.1)	6324.0(.2)	6339.7(.1)	6248.6(2.8)	3.4 (0.1)
4.69	6303.8(.1)	6319.6(.1)	6334.7(.1)	6256.3(1.6)	2.9 (0.1)
5.08	6308.7(.1)	6321.4(.1)	6335.1(.1)	6267.9(3.3)	2.5 (0.1)
5.47	6323.3(.1)	6324.9(.1)	6337.3(.1)	6276.2(2.8)	2.2 (0.1)
5.86	6320.1(.1)	6331.2(.1)	6342.2(.1)	6286.1(1.6)	2.1 (0.1)

NOTE - POLARISATION PARALLEL TO DIRECTION IN WHICH STRESS WILL BE APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 2. TRANSIT TIMES AT 21 MPa AS A FUNCTION OF FREQUENCY AND TEMPERATURE.

	MEASURED VALUES			CALCULATED VALUES	
TEMPERATURE	16.8C	21.9C TRANSIT TIMES	27.1C	OC TRANSIT TIME	TEMPERATURE COEFFICIENT NANOSEC/C
FREQUENCY MHz					
2.73	6317.4(.2)	6334.2(.1)	6351.3(.1)	6262.1(0.4)	3.3 (0.002)
3.13	6318.5(.1)	6332.8(.1)	6350.8(.1)	6265.2(4.2)	3.1 (0.2)
3.52	6328.9(.1)	6338.3(.1)	6354.1(.1)	6286.7(7.7)	2.4*(0.3)
3.91	6319.1(.2)	6332.9(.1)	6347.7(.2)	6272.3(0.9)	2.8*(0.04)
4.30	6300.4(.1)	6318.2(.1)	6334.4(.1)	6245.3(2.2)	3.3 (0.1)
4.69	6298.3(.1)	6312.4(.1)	6327.4(.1)	6250.7(0.8)	2.8 (0.03)
5.08	6301.9(.1)	6314.2(.1)	6328.1(.1)	6258.9(1.7)	2.5 (0.1)
5.47	6307.0(.1)	6318.0(.1)	6330.7(.1)	6268.0(1.8)	2.3 (0.1)
5.86	6314.5(.1)	6325.1(.1)	6336.8(.1)	6278.0(1.1)	2.2 (0.05)

NOTE - POLARISATION PARALLEL TO DIRECTION IN WHICH STRESS WAS APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 3. TRANSIT TIMES AT 38 MPa AS A FUNCTION OF FREQUENCY AND TEMPERATURE.

	MEASURED VALUES			CALCULATED VALUES	
TEMPERATURE	16.8C	22.1C TRANSIT TIMES	27.1C	OC TRANSIT TIME	TEMPERATURE COEFFICIENT NANOSEC/C
FREQUENCY MHz					
2.73	6311.4(.1)	6328.4(.1)	6345.9(.1)	6254.9(1.9)	3.3 (0.1)
3.13	6313.7(.1)	6328.7(.1)	6345.9(.2)	6257.8(3.9)	3.2 (0.2)
3.52	6323.7(.1)	6334.6(.1)	6349.2(.1)	6281.5(5.6)	2.5*(0.2)
3.91	6315.9(.1)	6329.7(.1)	6342.9(.2)	6271.8(0.2)	2.6 (0.01)
4.30	6295.4(.1)	6313.0(.1)	6328.6(.2)	6241.4(1.3)	3.2 (0.1)
4.69	6292.3(.1)	6306.1(.1)	6320.2(.1)	6246.6(1.4)	2.7 (0.1)
5.08	6296.3(.1)	6308.0(.1)	6320.8(.1)	6256.1(2.3)	2.4 (0.1)
5.47	6301.4(.1)	6312.3(.1)	6323.8(.1)	6264.7(1.6)	2.2 (0.1)
5.86	6309.2(.1)	6319.6(.1)	6331.0(.1)	6273.4(2.1)	2.1 (0.1)

NOTE - POLARISATION PARALLEL TO DIRECTION IN WHICH STRESS WAS APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 4. TRANSIT TIMES AT 68 MPa AS A FUNCTION OF FREQUENCY AND TEMPERATURE.

	MEASURED VALUES			CALCULATED VALUES	
TEMPERATURE	16.7C	22.0C TRANSIT TIMES	27.1C	0C TRANSIT TIME	TEMPERATURE COEFFICIENT NANOSEC/C
FREQUENCY MHz					
2.73	6303.9(.1)	6321.0(.2)	6338.4(.2)	6248.4(1.2)	3.3 (0.1)
3.13	6304.7(.1)	6321.4(.2)	6338.5(.2)	6250.3(1.3)	3.2 (0.1)
3.52	6315.2(.1)	6328.2(.1)	6342.2(.1)	6271.6(1.9)	2.6*(0.1)
3.91	6308.7(.2)	6323.2(.1)	6336.3(.1)	6264.5(1.1)	2.7 (0.05)
4.30	6286.6(.1)	6304.2(.1)	6321.8(.2)	6230.0(0.8)	3.4 (0.04)
4.69	6283.2(.1)	6295.8(.5)	6312.5(.1)	6235.4(5.8)	2.8*(0.3)
5.08	6287.4(.1)	6298.6(.1)	6313.2(.1)	6245.4(4.8)	2.5*(.02)
5.47	6293.0(.1)	6303.5(.1)	6316.5(.1)	6254.8(3.7)	2.3*(0.2)
5.86	6301.1(.1)	6311.7(.1)	6323.0(.1)	6265.8(1.4)	2.1 (0.1)

NOTE - POLARISATION PARALLEL TO DIRECTION IN WHICH STRESS WILL BE APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 5. TRANSIT TIMES AT ZERO STRESS AS A FUNCTION OF FREQUENCY AND TEMPERATURE.

	MEASURED VALUES			CALCULATED VALUES	
TEMPERATURE	18.2C	23.2C TRANSIT TIMES	28.4C	OC TRANSIT TIME	TEMPERATURE COEFFICIENT NANOSEC/C
FREQUENCY MHz					
2.73	6384.5(.1)	6397.6(.1)	6415.0(.2)	6329.4(5.0)	3.0 (0.2)
3.13	6394.9(.2)	6406.3(.1)	6416.9(.1)	6357.6(2.8)	2.1 (0.1)
3.52	6399.9(.2)	6412.4(.1)	6420.5(.2)	6364.0(6.4)	2.0 (0.3)
3.91	6382.4(.1)	6397.9(.1)	6413.6(.2)	6326.8(0.5)	3.1 (0.02)
4.30	6362.9(.2)	6380.6(.1)	6397.0(.1)	6302.4(2.6)	3.3 (0.1)
4.69	6362.7(.1)	6376.7(.1)	6392.6(.1)	6309.9(1.8)	2.9 (0.1)
5.08	6361.2(.1)	6372.6(.1)	6386.0(.1)	6316.7(2.0)	2.4 (0.1)
5.47	6358.9(.1)	6370.6(.1)	6382.0(.1)	6317.8(1.0)	2.3 (0.04)
5.86	6371.5(.1)	6382.8(.1)	6392.8(.1)	6333.8(2.3)	2.1 (0.1)

NOTE - POLARISATION PARALLEL TO DIRECTION IN WHICH STRESS WILL BE APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 6. TRANSIT TIMES AT 21 MPa AS A FUNCTION OF FREQUENCY AND TEMPERATURE. LEAST SQUARES FIT TO DATA NOT CALCULATED

	MEASURED VALUES	
TEMPERATURE	18.4C	23.4C
FREQUENCY MHz		
2.73	6386.1(.1)	6398.9(.2)
3.13	6396.4(.1)	6407.4(.1)
3.52	6402.5(.2)	6414.4(.1)
3.91	6383.4(.1)	6399.2(.2)
4.30	6364.4(.2)	6381.6(.2)
4.69	6363.9(.1)	6377.8(.1)
5.08	6362.1(.1)	6372.8(.1)
5.47	6360.7(.1)	6371.3(.1)
5.86	6373.0(.1)	6383.4(.1)

NOTE - POLARISATION PERPENDICULAR TO DIRECTION IN WHICH STRESS WAS APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 7. TRANSIT TIMES AT 38 MPA AS A FUNCTION OF FREQUENCY AND TEMPERATURE. LEAST SQUARES FIT TO DATA NOT CALCULATED.

	MEASURED VALUES	
TEMPERATURE	18.3C	23.3C
FREQUENCY MHz		
2.73	6386.4(.1)	6398.2(.3)
3.13	6397.4(.1)	6406.6(.1)
3.52	6403.1(.1)	6415.0(.2)
3.91	6384.8(.2)	6399.8(.2)
4.30	6364.7(.1)	6382.7(.2)
4.69	6364.8(.1)	6378.3(.1)
5.08	6362.6(.1)	6373.2(.1)
5.47	6362.0(.1)	6372.3(.1)
5.86	6373.8(.1)	6383.9(.1)

NOTE - POLARISATION PERPENDICULAR TO DIRECTION IN WHICH STRESS WAS APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 8. TRANSIT TIMES AT 68 MPa AS A FUNCTION OF FREQUENCY AND TEMPERATURE

	MEASURED VALUES			CALCULATED VALUES	
TEMPERATURE	18.3C	23.4C TRANSIT TIMES	28.3C	OC TRANSIT TIME	TEMPERATURE COEFFICIENT NANOSEC/C
FREQUENCY MHz					
2.73	6387.9(.2)	6399.2(.2)	6417.0(.2)	6333.6(9.7)	2.9*(0.4)
3.13	6399.5(.2)	6406.9(.1)	6419.0(.1)	6363.0(7.0)	1.9*(0.3)
3.52	6404.9(.1)	6416.9(.1)	6424.8(.1)	6369.0(5.1)	2.0*(0.2)
3.91	6387.0(.1)	6402.5(.2)	6418.4(.2)	6329.4(1.4)	3.1 (0.1)
4.30	6366.5(.2)	6385.2(.2)	6400.7(.2)	6304.3(3.4)	3.4 (0.1)
4.69	6366.3(.1)	6381.2(.1)	6395.9(.1)	6312.1(0.5)	3.0 (0.02)
5.08	6364.2(.1)	6375.6(.1)	6389.6(.1)	6317.2(4.3)	2.5 (0.2)
5.47	6364.0(.1)	6374.9(.1)	6386.9(.1)	6321.9(2.1)	2.3 (0.1)
5.86	6375.6(.1)	6386.8(.1)	6397.1(.1)	6336.3(0.7)	2.2 (0.03)

NOTE - POLARISATION PARALLEL TO DIRECTION IN WHICH STRESS WAS APPLIED. VALUES GIVEN IN NANOSEC WITH STANDARD ERROR OF MEAN IN BRACKETS. ALSO GIVEN ARE THE TRANSIT TIMES AT ZERO DEGREES, THE TEMPERATURE COEFFICIENTS AND IN BRACKETS THE STANDARD ERROR OF THESE VALUES CALCULATED USING A LEAST SQUARES LINEAR FIT. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

TABLE 9. INTERPOLATED VALUES OF TRANSIT TIMES AT 22C AT THE FOUR STRESS LEVELS FOR EACH POLARIZATION. FURTHER LINEAR LEAST SQUARES FIT OF DIFFERENTIAL TRANSIT TIME AGAINST STRESS AT EACH FREQUENCY HAS BEEN USED TO DERIVE THE ACOUSTOELASTIC CONSTANTS. THE COEFFICIENTS OF DETERMINATION ARE ALL BETTER THAN 0.995 EXCEPT FOR THOSE CASES INDICATED BY *.

FREQUENCY	STRESS	TRANSIT TIMES POLARIZATION PARALLEL NANOSEC	TRANSIT TIMES POLARIZATION DIRECTIONS PERPENDICULAR NANOSEC	DIFFERENTIAL TRANSIT TIME NANOSEC	ZERO STRESS DIFFERENTIAL TRANSIT TIME NANOSEC	COEFFICIENTS NANOSEC/MPa	ACOUSTOELASTIC CONSTANT MPa^{-1}
2.73	0	6339.1	6395.2	56.1	55.4	0.30*	$4.7 * 10^{-5}$
	21	6334.5	6395.3	60.8			
	38	6328.6	6395.1	66.5			
	68	6321.4	6397.5	76.1			
	0	6339.1	6403.1	64.0	64.0	0.30	$4.7 * 10^{-5}$
	21	6334.2	6404.3	70.1			
	38	6329.0	6404.2	75.2			
	68	6321.8	6405.8	84.0			
3.52	0	6344.8	6408.4	63.6	64.0	0.30	$4.7 * 10^{-5}$
	21	6340.6	6411.1	70.5			
	38	6335.9	6411.9	76.0			
	68	6328.7	6412.8	84.1			
3.91	0	6337.1	6394.1	57.0	56.3	0.28*	$4.4 * 10^{-5}$
	21	6333.4	6394.8	61.4			
	38	6329.5	6395.9	66.4			
	68	6322.9	6398.5	75.6			
4.30	0	6322.9	6315.9	53.0	52.7	0.33	$5.2 * 10^{-5}$
	21	6317.9	6376.8	58.9			
	38	6312.3	6378.0	65.7			
	68	6304.5	6379.6	75.1			
4.69	0	6319.8	6373.6	53.8	53.8	0.39	$6.1 * 10^{-5}$
	21	6312.9	6373.9	61.0			
	38	6306.2	6374.8	68.6			
	68	6297.3	6377.2	79.9			
5.08	0	6322.1	6370.2	48.1	47.7	0.37	$5.8 * 10^{-5}$
	21	6314.9	6369.8	54.9			
	38	6308.4	6370.4	62.0			
	68	6299.9	6373.0	73.1			
5.47	0	6325.3	6367.6	42.2	42.1	0.38	$6.0 * 10^{-5}$
	21	6318.6	6368.3	49.7			
	38	6312.5	6369.6	57.1			
	68	6304.5	6372.3	67.8			
5.86	0	6331.5	6379.7	48.2	48.0	0.35	$5.4 * 10^{-5}$
	21	6325.6	6380.5	54.9			
	38	6319.9	6381.3	61.4			

TABLE 10. MULTIPLE LINEAR REGRESSION FIT OF TRANSIT TIME AS FUNCTION OF TEMPERATURE AND STRESS AT EACH FREQUENCY ACCORDING TO RELATIONSHIP. TRANSIT TIME = A*TEMP. + B* STRESS + C. STANDARD ERROR ESTIMATES GIVEN IN BRACKETS. POLARIZATION PARALLEL TO DIRECTION OF STRESS.

FREQUENCY MHz	A NANOSEC/C	B NANOSEC/MPa	C NANOSEC
2.73	3.4(0.1)	-0.27(0.01)	6265.5(1.1)
3.13	3.1(0.1)	-0.26(0.01)	6270.5(1.7)
3.52	2.4(0.1)	-0.24(0.02)	6291.3(2.6)
3.91	2.7(0.05)	-0.21(0.01)	6277.1(1.0)
4.30	3.3(0.04)	-0.27(0.01)	6250.0(1.0)
4.69	2.8(0.1)	-0.33(0.01)	6257.8(1.4)
5.08	2.5(0.1)	-0.33(0.01)	6267.5(1.5)
5.47	2.2(0.1)	-0.31(0.01)	6275.8(1.3)
5.86	2.1(0.04)	-0.29(0.01)	6285.0(0.8)

TABLE 11. MULTIPLE LINEAR REGRESSION FIT OF TRANSIT TIME AS FUNCTION OF TEMPERATURE AND STRESS AT EACH FREQUENCY ACCORDING TO RELATIONSHIP TRANSIT TIME = A*TEMP. + B*STRESS + C. STANDARD ERROR ESTIMATES GIVEN IN BRACKETS. POLARISATION PERPENDICULAR TO DIRECTION OF STRESS.

FREQUENCY MHz	A NANOSEC/C	B NANOSEC/MPa	C NANOSEC
2.73	2.9(0.1)	0.03(0.02)	6331.8(3.0)
3.13	2.0(0.1)	0.03(0.01)	6358.9(1.8)
3.52	2.0(0.1)	0.06(0.01)	6363.8(2.4)
3.91	3.1(0.04)	0.07(0.01)	6325.1(0.9)
4.30	3.4(0.1)	0.06(0.01)	6300.6(1.2)
4.69	2.9(0.05)	0.05(0.01)	6308.8(1.1)
5.08	2.5(0.1)	0.05(0.01)	6315.6(2.0)
5.47	2.3(0.04)	0.07(0.01)	6317.7(1.0)
5.86	2.1(0.04)	0.06(0.01)	6332.7(0.8)

TABLE 12. MULTIPLE LINEAR REGRESSION FIT OF RELATIONSHIP TRANSIT TIME = A*TEMP. + B*STRESS + C + D*STRESS*TEMP. STANDARD ERROR ESTIMATES GIVEN IN BRACKETS. POLARIZATION PARALLEL TO DIRECTION OF STRESS.

FREQUENCY MHz	A NANOSEC/C	B NANOSEC/MPa	C NANOSEC	D NANOSEC/C.MPa
2.73	3.4(0.1)	-0.23(0.04)	6264.2(1.8)	-0.002(0.002)
3.13	3.0(0.1)	-0.33(0.06)	6272.8(2.5)	0.003(0.003)
3.52	2.3(0.2)	-0.34(0.10)	6294.4(4.0)	0.004(0.004)
3.91	2.9(0.1)	-0.13(0.03)	6274.5(1.3)	0.004(0.001)
4.30	3.3(0.1)	-0.27(0.04)	6250.0(1.7)	-0.000(0.002)
4.69	2.8(0.1)	-0.30(0.05)	6256.9(2.3)	-0.001(0.002)
5.08	2.5(0.1)	-0.32(0.06)	6267.3(2.5)	-0.000(0.003)
5.47	2.2(0.1)	-0.31(0.05)	6275.7(2.2)	-0.000(0.002)
5.86	2.1(0.1)	-0.29(0.03)	6285.2(1.4)	0.000(0.001)

TABLE 13. MULTIPLE LINEAR REGRESSION FIT OF RELATIONSHIP TRANSIT TIME = A*TEMP + B*STRESS + C + C*STRESS*TEMP. STANDARD ERROR ESTIMATES GIVEN IN BRACKETS. POLARIZATION PERPENDICULAR TO DIRECTION OF STRESS.

FREQUENCY MHz	A NANOSEC/C	B NANOSEC/MPa	C NANOSEC	D NANOSEC/C.MPa
2.73	2.9(0.2)	0.06(0.11)	6331.0(4.8)	-0.001(0.005)
3.13	2.1(0.1)	0.08(0.07)	6357.5(2.9)	-0.002(0.003)
3.52	2.1(0.2)	0.07(0.09)	6363.5(3.8)	-0.000(0.004)
3.91	3.1(0.1)	0.05(0.03)	6325.8(1.3)	0.001(0.001)
4.30	3.4(0.1)	0.03(0.04)	6301.4(1.8)	0.001(0.002)
4.69	2.9(0.1)	0.04(0.04)	6309.1(1.7)	0.000(0.002)
5.08	2.4(0.1)	0.01(0.07)	6316.8(3.1)	0.002(0.003)
5.47	2.3(0.1)	0.06(0.03)	6317.9(1.6)	0.000(0.002)
5.86	2.1(0.1)	0.04(0.03)	6333.4(1.3)	0.001(0.001)

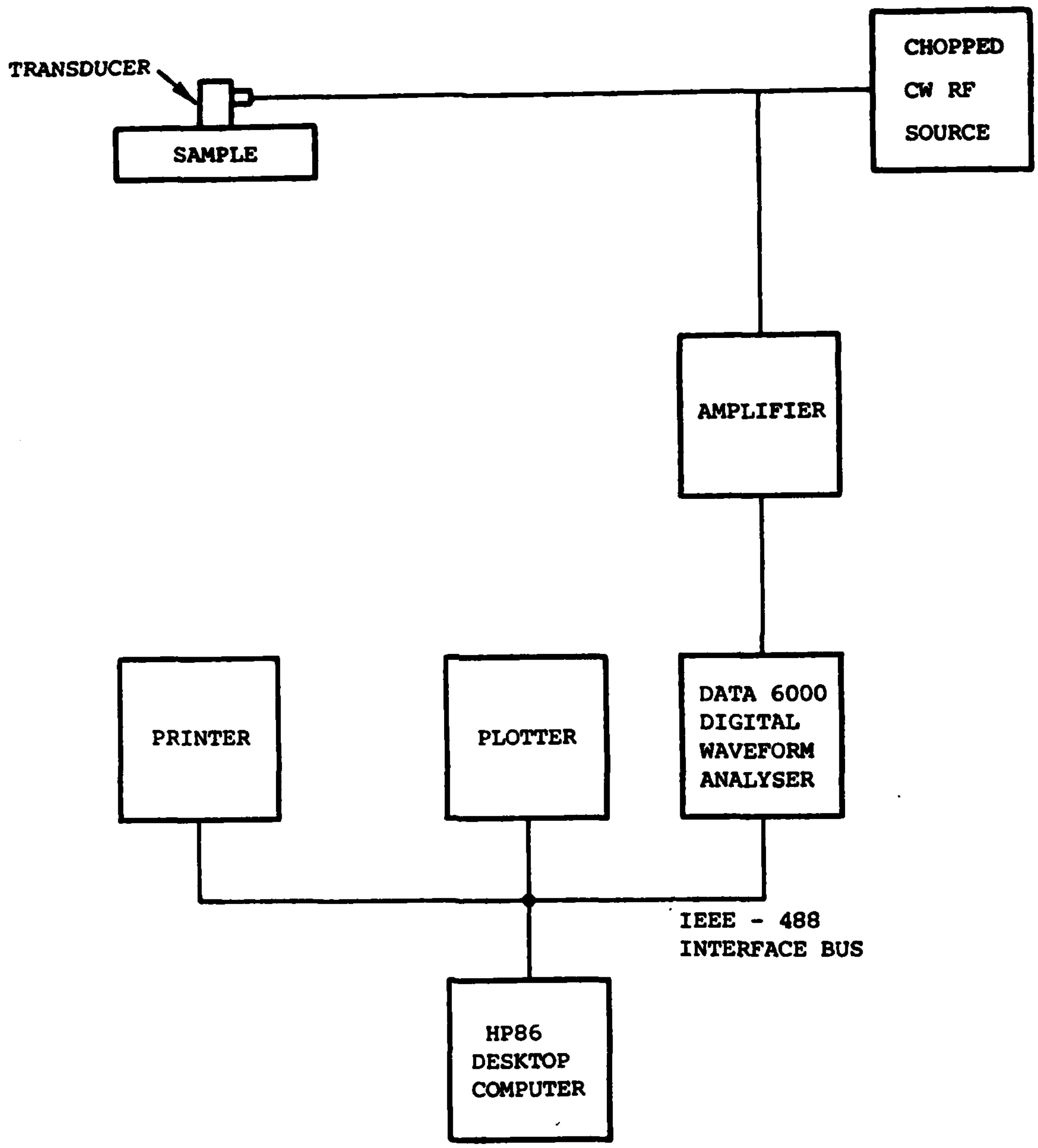

FIG. 1 BLOCK DIAGRAM OF EXPERIMENTAL ARRANGEMENT

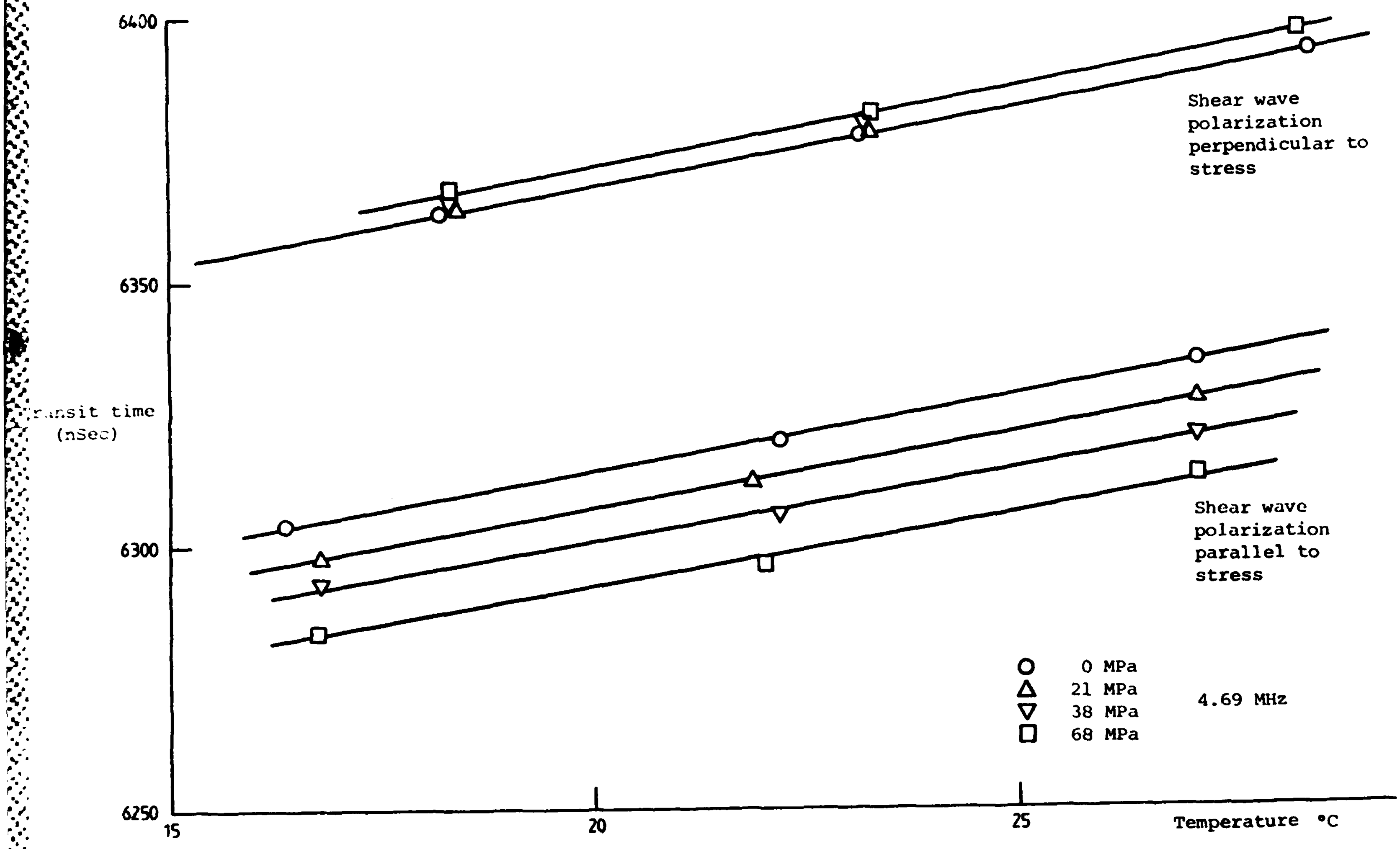

FIG. 2 TRANSIT TIMES AS A FUNCTION OF STRESS AND TEMPERATURE

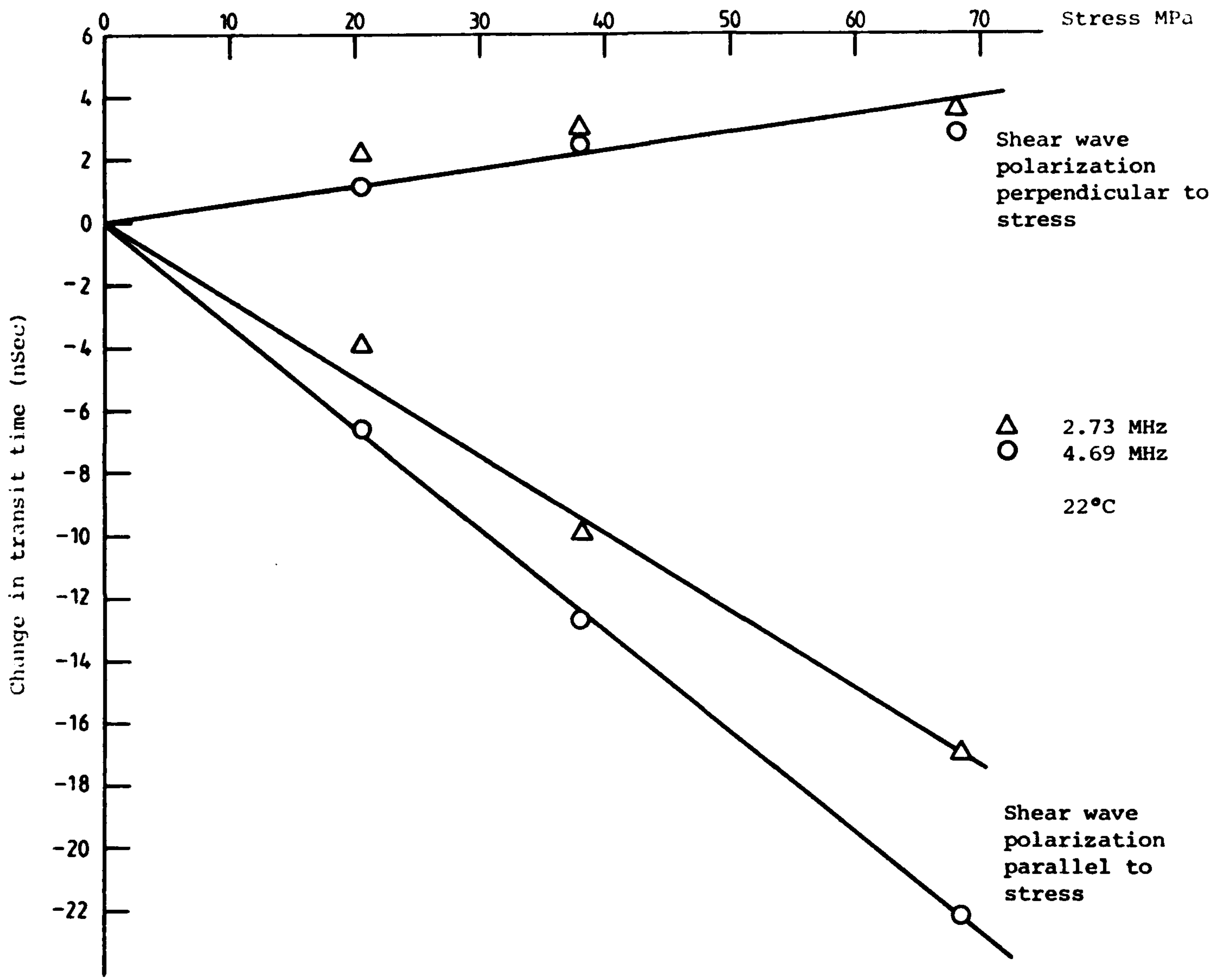

FIG. 3 CHANGE FROM ZERO STRESS VALUE OF THE TRANSIT TIME AS A FUNCTION OF STRESS

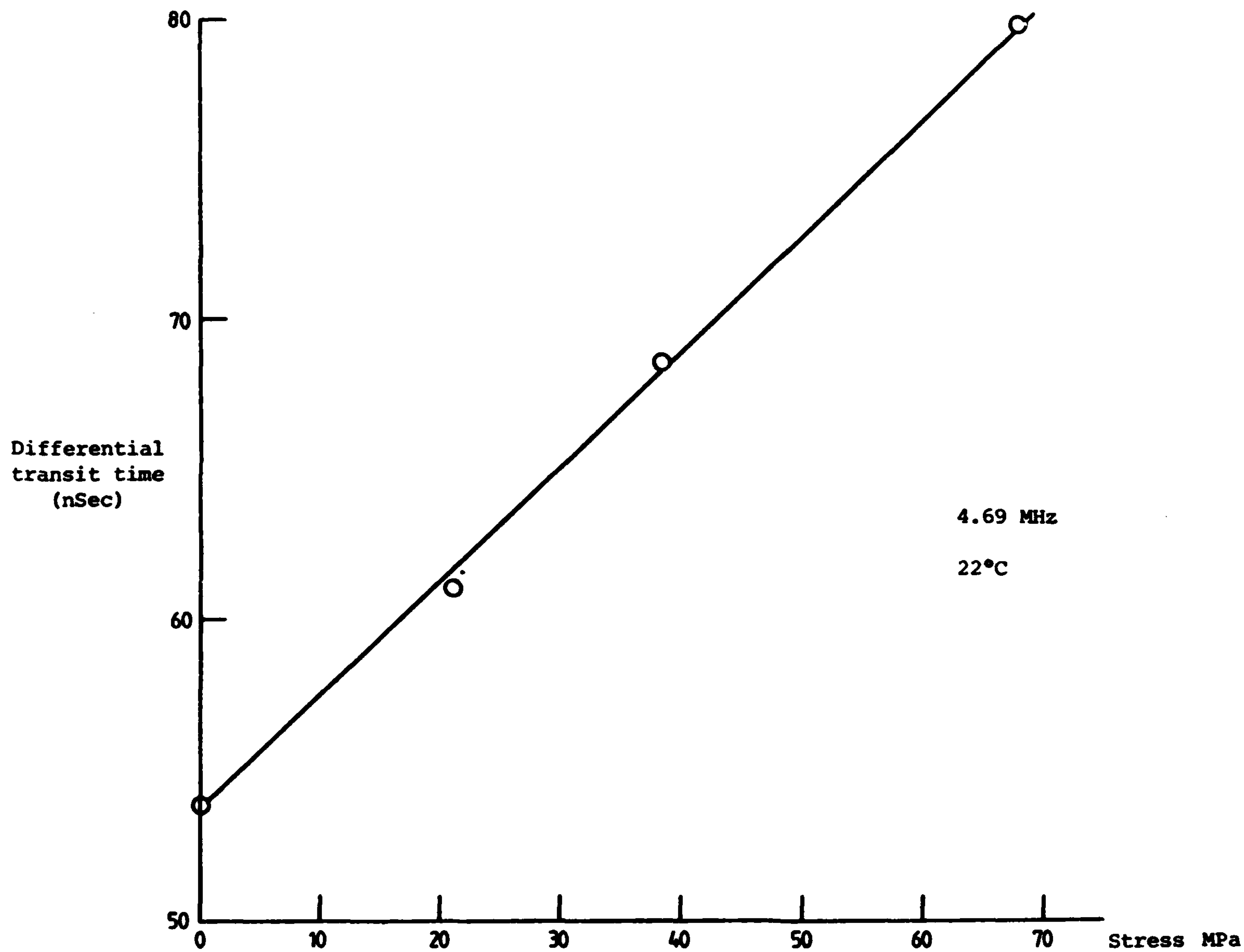

FIG. 4 DIFFERENTIAL TRANSIT TIME AS A FUNCTION OF STRESS

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Ultrasonics Temperature Stresses Time measurement S waves Transit times	20010

16. Abstract

The practical use of ultrasonics to determine residual stress requires a technique to separate the effects of texture and stress. This memorandum reports the results of a preliminary study of the temperature, stress and frequency dependence of ultrasonic shear wave transit times in a 2024T4 aluminium alloy sample. The acoustoelastic constant, the relative temperature coefficient and the texture induced anisotropy were found to be of the order 10^{-4}/MPa, 10^{-3}/K and 10^{-2} respectively.

(0.001) (0.01) (0.0001)

Two techniques of separating the effects of texture and stress were investigated. These were the stress dependence of temperature coefficient and the frequency dependence of the →

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16. Abstract (Contd)

birefringence. It was found that, within the precision of measurement, there was no stress dependence of the temperature coefficient for shear wave polarization parallel or perpendicular to the stress. The frequency dependence had a complex behaviour which is not yet understood, and will be the subject of further study.

Keywords: Stresses, Time measurement; S waves; Transit times. (Australia)

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